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NONLINEAR PREDICTION CONCEPT
FOR IMPROVING GUN ACCURACY

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13. ABSTRACT (Maximum 200 words)

The purpose of a gun fire control system is to offset the gun from the target line-of-sight such that a projectile will impact the target at a time of flight later. This report investigates a prediction concept for improving gun-to-target offsets against maneuvering targets. The accuracy of a predictor is measured by its ability to predict the position of a target at a time of flight later. Prediction of future position is a function of present motion of the target and time of flight of the projectile. The performance of the predictor depends on how accurately the assumed target states characterize the actual motion. For maneuvering targets, the existence of target acceleration and/or higher derivatives of the motion degrades the performance of a linear predictor thus creating the requirement for nonlinear prediction. Analyses are presented for classical first- and second-order predictors, and for a curvilinear prediction concept. The rationale and preliminary results are presented which indicate that the curvilinear concept has more potential than a classical second-order predictor for improving the performance of gun fire control systems against maneuvering targets.

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NONLINEAR PREDICTION CONCEPT FOR IMPROVING GUN ACCURACY

1. INTRODUCTION

The maneuvering tactics of airplanes, helicopters and ground vehicles, whether performed to enhance survivability or to carry out their mission, have significantly degraded the performance capability of conventional gun systems to engage these targets. An improved fire control solution is obviously the answer; however, this means predicting more accurately the future position of an uncooperative target.

The purpose of a gun fire control system engaging non-stationary targets is to offset the gun from the target line-of-sight such that a ballistic round will impact the target at a time of flight later. The required functions for the fire control system to generate this gun-to-target offset, defined as the lead angle, are target tracking, estimating the present target states, and predicting future target position. A fourth required function is to stabilize the gun about the commanded offset. These functions are necessary but not sufficient conditions for achieving the correct gun-to-target offset. The tracking and estimation processes and gun stabilization could be perfect, but the projectile may still miss the target. This probable miss is caused by the target induced error, resulting from actual target motion being different from that predicted over the projectile's time of flight.

The objective of this report is to describe a novel prediction concept[1,2] for improving the gun-to-target offset against maneuvering targets. Analytically, the performance of a predictor can be defined by the accuracy of the predicted position relative to the actual target position at a time of flight later. Prediction of future position depends on present target motion, time of flight of the projectile for future target range and assumed target model dynamics for characterizing the actual motion. Although tracking, estimation and gun-stabilization errors propagate into prediction errors, emphasis is on prediction issues and a concept for improving gun-to-target offset against maneuvering targets. The existence of acceleration in maneuvering target motion clearly nullifies the constant velocity or rate assumption of linear predictors.

Analyses are presented for classical first- and second-order predictors, and for the proposed curvilinear prediction concept. Rationale and results are presented which indicate that the curvilinear concept has the greatest potential for improving the performance of gun fire control systems engaging maneuvering targets.

2. PREDICTION ISSUES AND CONCEPTS

Current predictive gun fire control systems exhibit degraded performance when engaging maneuvering targets, both ground and airborne. The main reason for the degraded performance is that the fire control system is not capable of accurately predicting the position of the maneuvering target over the time-of-flight of the projectile.

A criterion often used to evaluate/quantify the performance of a gun fire control system is total gun pointing (TGP) error. The TGP error is defined as the difference between the actual gun pointing direction at round exit and the line-of-sight of the target at a time-of-flight later. The inaccuracy of gun pointing is caused by systematic or system induced (SI) errors, and unaccounted target motion after round exit or target induced (TI) errors. The propagation of systematic errors, such as tracking errors, through the estimation and prediction processes has a major influence on the accuracy of the fire control solution.[3,4] Although minimizing the SI errors is critical to the solution, the issues in this report are focused on the TI errors, relative to maneuvering targets.

The assumption of constant target states, e.g., velocity, acceleration, over the time-of-flight of the projectile is an unavoidable constraint for obtaining a mathematical or realizable solution. By definition, a maneuvering target has components of acceleration. Unfortunately, as a rule these accelerations are either not taken into account by the prediction process or not adequately represented in the prediction concept. The linear, first-

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order predictor assumes a constant velocity, hence zero acceleration. The second-order, quadratic, predictor assumes the acceleration to be constant which constrains the target path to be parabolic.

A very important issue, which is often neglected, is the coordinate system used to predict future target position. This issue is illustrated in the following description of linear prediction. For this discussion, target motion is assumed to be in a horizontal plane.

Conventional linear, often referred to as first-order, prediction is a function of target velocity and projectile time-of-flight as defined by the state equation:

$$\underline{X}_f = \underline{X}_p + \underline{V}_p \, t_{of}$$

where $\underline{X}_f$ is the future target position, $\underline{X}_p$ is the present position and $\underline{V}_p$ is present target velocity in two dimensional space, and t_{of} is projectile's time-of-flight. In a cartesian coordinate system, the linear predictor assumes that target speed and heading are constant for a time duration t_{of}; thus the target moves in a straight line. In line-of-sight coordinates, linear prediction assumes that the target is moving along a circle whose radius is the target range (constant) from the gun system, with constant angular rate in a fixed plane, as defined by the equation (scalar in the assumed horizontal plane):

$$\phi_f = \phi_p + \dot{\phi}_p \, t_{of}$$

where ϕ_p and ϕ_f are present and future angular positions, and $\dot{\phi}_p$ is present angular rate of target in the reference coordinate system.

The conventional second-order or quadratic predictor is a function of the target's position, velocity, and acceleration. Again for simplicity, the motion is confined to a horizontal plane. The prediction of the target's future position is defined via the equation:

$$\underline{X}_f = \underline{X}_p + \underline{V}_p \, t_{of} + 1/2 \underline{A}_p \, t_{of}^2$$

where $\underline{X}_f$, $\underline{X}_p$, $\underline{V}_p$, and t_{of} are the same as for the first-order predictor and $\underline{A}_p$ is the present acceleration in cartesian coordinates. The second-order predictor assumes that the target travels along a parabolic path in each direction.

The curvilinear concept is proposed as a technique for improving the performance of predictive gun fire control systems. The curvilinear or nonlinear predictor reduces the TI errors by realistically characterizing the motion of a maneuvering target. Acceleration occurs from either a change in magnitude or direction of the velocity vector. Laws of aerodynamics and the requirement to maintain a stable operating condition while maneuvering constrain the orientation of acceleration for an aircraft to be in a direction that is essentially perpendicular to the longitudinal axis of the maneuvering vehicle, which is nominally aligned with its velocity vector. Similarly, Ackerman steering on wheeled vehicles and differential tread movement on tracked vehicles produce dominant acceleration for evasive mobility by changing the direction of the velocity vector. The analysis of a previous study [5] showed that the acceleration of maneuvering targets results more from rotational motion than translational motion. Based on these assertions, the target path over finite time intervals of the maneuver is considered to be along a circular arc. Another important feature of the curvilinear concept is that the motion is defined in a vehicle-oriented coordinate system.

For the curvilinear predictor, the target's future position is given by the equation:

$$\underline{X}_f = \underline{X}_p + \gamma_V \underline{V}_p \, t_{of} + 1/2 \, \gamma_A \underline{A}_p \, t_{of}^2$$

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where the factors γ_V and γ_A account for the rotational motion of target (a circular arc) during the projectile's time of flight. They are derived from the power series expansions of the sine and cosine functions, and defined by the expressions[1]:

$$\gamma_V = 1 - (\omega \, t_{of})^2 \, /6,$$

$$\gamma_A = 1 - (\omega \, t_{of})^2 \, /12$$

where ω is the turning, rotational, rate of the target in a vehicular-oriented coordinate system. For a circular arc ω is equal to the magnitude of the normal acceleration divided by the magnitude of the velocity. The target motion during the time of flight is constrained to a maneuver plane. For ground vehicles this plane is basically horizontal; for airborne targets, the maneuver plane as defined by the velocity and acceleration vectors is a fixed two-dimensional plane but oriented in three-dimensional space. Thus, the maneuver plane is in a cartesian frame referenced to the target, and the future position is predicted in this plane. For assumed target motion along an arc of a circle in a horizontal plane, the two-dimensional equation in vehicular coordinates is:

$$\begin{bmatrix} x \\ y \end{bmatrix}_f = \begin{bmatrix} x \\ y \end{bmatrix}_P + \gamma_V \begin{bmatrix} V \\ O \end{bmatrix}_P t_{of} + 1/2 \, \gamma_A \begin{bmatrix} O \\ A_N \end{bmatrix} t_{of}^2$$

where V = speed of target
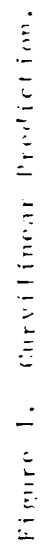 A_N = normal acceleration

Figure 1 illustrates this prediction concept. The fire control system (FCS) is assumed to be located at the origin of an earth oriented coordinate system (X_E - Y_E). From the measured target range, R, and line-of-sight angle, θ, it is assumed that the FCS can estimate the target's velocity and acceleration components in the earth frame. The orientation of the velocity vector relative to the earth coordinate system is defined by the heading angle. ψ. These estimates are transformed through ψ to define the target coordinate system. The velocity is aligned along the x-axis and normal acceleration is aligned along the y-axis of this target coordinate system. The future target position is predicted in this cartesian coordinate frame. In Figure 1 ΔX_t and ΔY_t are the predicted positions in the target coordinate frame. The predicted target position is then transformed back to the earth coordinate system where the lead angle of the gun is computed.

3. ANALYSIS OF RESULTS

The performances of the three defined predictors are evaluated by comparing the prediction, or target induced, errors for maneuvering target engagements. Two analytical paths and an actual path from a field test of a maneuvering M-60 tank are used in the analysis.

One of the analytical paths is produced from a stochastic model that generated maneuvering paths of ground vehicles.[6] The vehicular speed is constant (between 5 and 10 meters/second) for relatively long time intervals with speed changing several times over the duration of the path. The maximum lateral acceleration in the vehicular coordinate system is 0.2g, but most of the time the acceleration level was much lower. The other analytical path is a set of circular arcs for representing turning maneuvers of different type targets. For these analytical paths, the target states (position, velocity, and acceleration) are known quantities.

The path from the field tests, referred to as the ATMT path, is the motion of an M60 tank which performed a series of intentional maneuvers, e.g., turns and serpentine motion, in a random pattern. The measurements were X- and Y-positional data of the tank in a reference cartesian frame and recorded at a data rate of 10 times/second. The uncertainity in the position of the tank was advertised as 0.1 meters in each axis. The target states were estimated with an adaptive Kalman filter.[4]

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$$\psi = \cos^{-1}\left|\frac{V_x}{V}\right|$$

$$V = \sqrt{V_x^2 + V_y^2}$$

$$\Delta X_t = V t_{td}\left[1 - \frac{(\omega t_{td})^2}{6}\right]$$

$$\Delta Y_t = 1/2\, V \omega t_{td}^2\left[1 - \frac{(\omega t_{td})^2}{12}\right]$$

Figure 1. Curvilinear Prediction.

The prediction errors for the analytical path generated by the stochastic model are compared in Table 1. The time of flight is assumed to be 2.0 seconds.

TABLE 1. COMPARISON OF PREDICTION ERRORS FOR THE ANALYTICAL PATH

PREDICTOR	ONE-SIGMA ERROR (METERS)
LINEAR	1.6
QUADRATIC	0.7
CURVILINEAR	0.7

The second-order and curvilinear predictors are significantly better than the first-order predictor. The equal performance of the second-order and curvilinear predictors is due to the mild-maneuvering motion of this path. The simulated vehicular path is shown in Figure 2.

The paths described by circular arcs are analyzed to compare the lower-bound prediction errors of the second-order and curvilinear predictors. The underlying assumption is that a target maneuver can be represented by a circular arc over the projectile's time-of-flight, two seconds in these examples. The results are shown in Table 2.

TABLE 2. COMPARISON OF PREDICTION ERRORS FOR CIRCULAR PATHS

TARGET PARAMETERS			1-SIGMA ERRORS (METERS)	
SPEED (M/SEC)	LATERAL ACCELERATION (M/SEC/SEC)	TURNING RATE (RAD/SEC)	QUADRATIC	CURVILINEAR
1. 10.0	2.0	0.2	0.4	0.0
2. 10.0	4.0	0.4	1.5	<0.1
3. 15.0	9.0	0.6	5.0	0.4
4. 50.0	5.0	0.1	0.4	0.0
5. 250.0	50.0	0.2	8.2*	<0.1

*The mean values of the prediction errors are either zero or small compared to the 1-sigma error except for this case which had a mean of 4.3 meters.

The curvilinear predictor provides the best performance for all the conditions in Table 2.. The first two sets of conditions are representative of a ground vehicle; the third set is considered to represent a highly mobile ground vehicle. The fourth and fifth sets of conditions are representative of a helicopter and a fixed-wing airplane, respectively. The results are not surprising since curvilinear prediction is based on circular motion. The results for the second-order predictor illustrate that the distance traveled along a curved path can be a major factor in the magnitude of the TI error. In cases 1 and 5 the angular displacement of the target over the time-of-flight is the same but the fire control solution based on quadratic prediction for case 5 would result in the projectile not hitting an aircraft in a sustained 5g turn which is within the capability of modern tactical aircraft.

The results for the ATMT path are inconclusive for comparing the TI errors of different predictors. The results, shown in Table 3, illustrate the importance of minimizing systematic errors. Inaccuracies in the estimated target states can offset the capability of a prediction concept to reduce the TI errors. Although the accuracy of the ATMT path data is on the order of 0.2 meter (not 0.1 meter as advertised) in each component
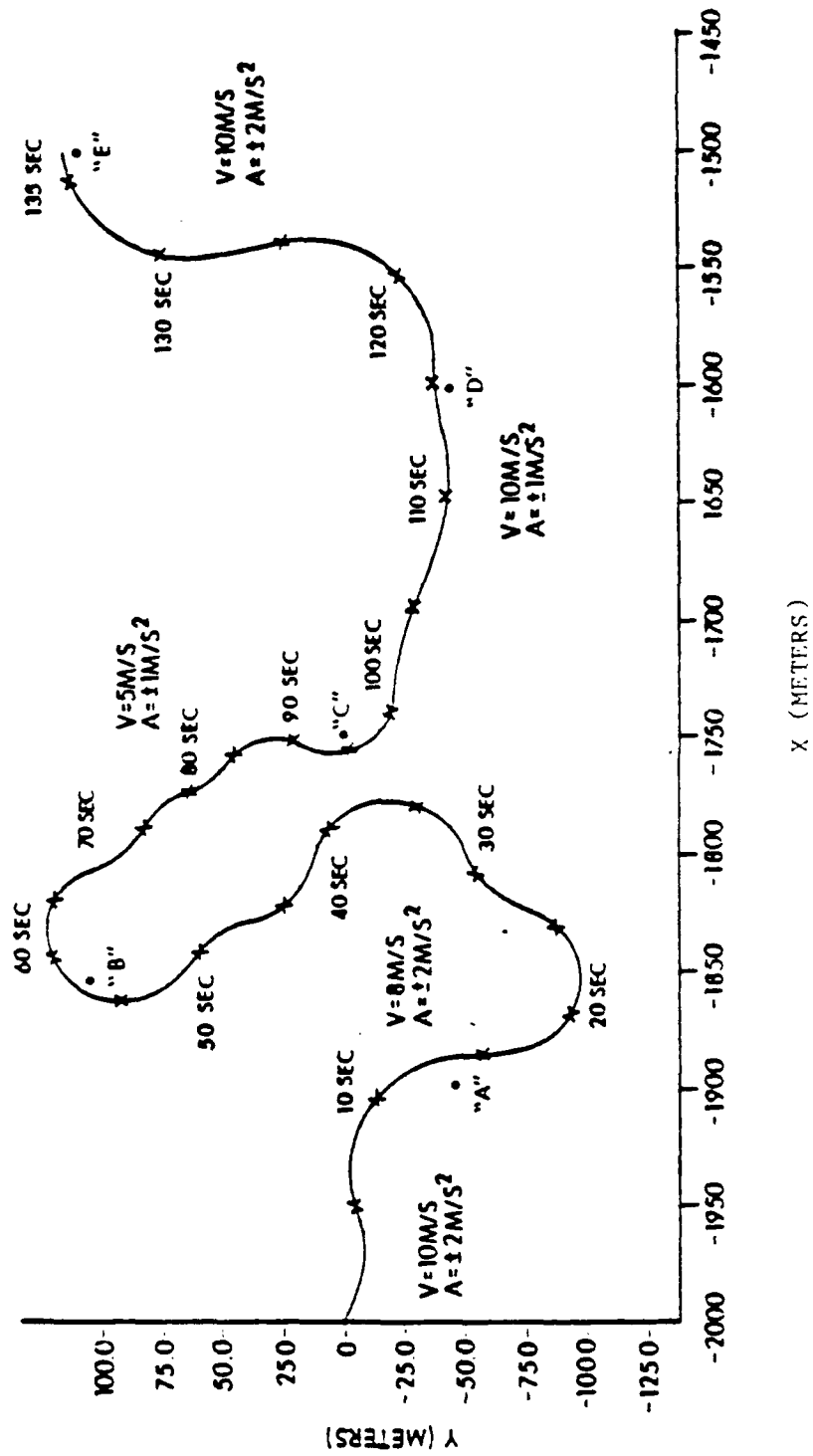
Figure 2. Analytically Generated Maneuvering Vehicle Path

position, the estimates of the vehicle's velocity and acceleration are not good enough to take advantage of prediction concepts which have the capability to reduce the TI error. Figures 3 and 4 show the estimates of target speed and acceleration which were obtained with an adaptive Kalman filter.[4] Results from previous analyses/studies[7,8] indicate that tracking accuracy of less than 0.1 mrad are required in order to obtain the improved performance of nonlinear predictors.

TABLE 3. PERFORMANCE COMPARISONS FOR THE ATMT PATH

PREDICTION ERROR FOR 2 SECONDS TIME OF FLIGHT

CONCEPT	1-SIGMA ERRORS (METERS)
NO PREDICTION	5.2 (MEAN: 1.8)
LINEAR	4.5
QUADRATIC	5.7
CURVILINEAR	5.0

4. CONCLUSIONS

The velocities and accelerations of maneuvering vehicles are closely aligned respectively with the longitudinal and lateral axes of the vehicle. Gun fire-control systems performance may be improved when maneuvering targets are engaged with a prediction algorithm that takes advantage of the fact that the predominant acceleration is caused by rotational motion. During a projectile's time of flight, motion relative to a coordinate system fixed to the vehicle axes is better described by a circular arc than a parabolic.

The results from the analysis of the curvilinear prediction concept are encouraging. Accurate target states of actual vehicular motion are required to completely evaluate the concept. The curvilinear predictor has the greatest potential for reducing the target induced errors caused by the rotational motion of a maneuvering target. Consequently, prediction should be accomplished in cartesian coordinates aligned with the vehicular referenced frame where the forces are acting to produce the maneuver dynamics.

The design of a fire control system with the curvilinear predictor will require improved tracking and target state estimates. In addition to the angular measurements from the tracking system, accurate range or range rate measurements are essential for improving performance of predictive gun systems engaging maneuvering targets. Sensors capable of measuring vehicular heading or turning rate would greatly enhance the performance of the curvilinear concept.
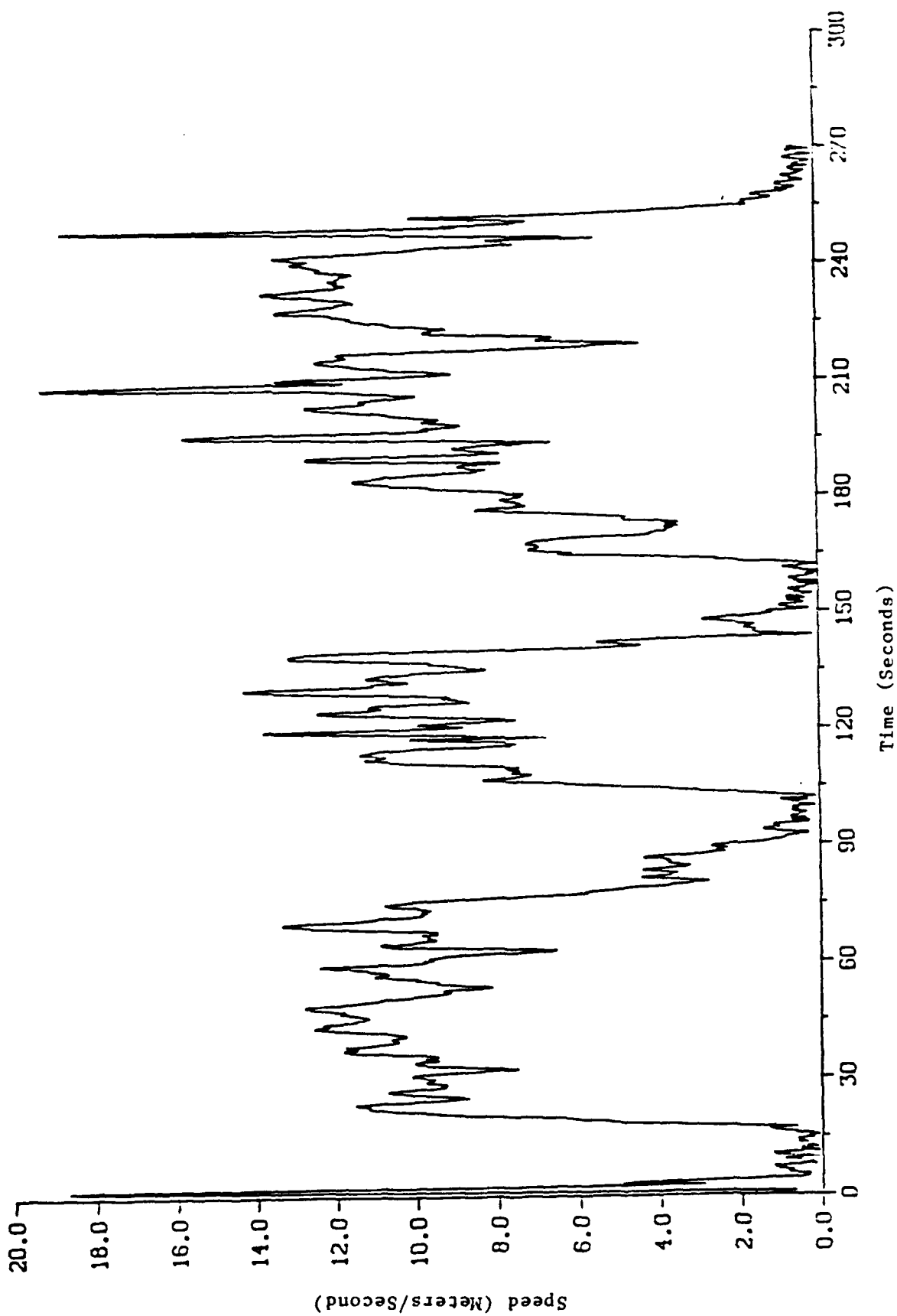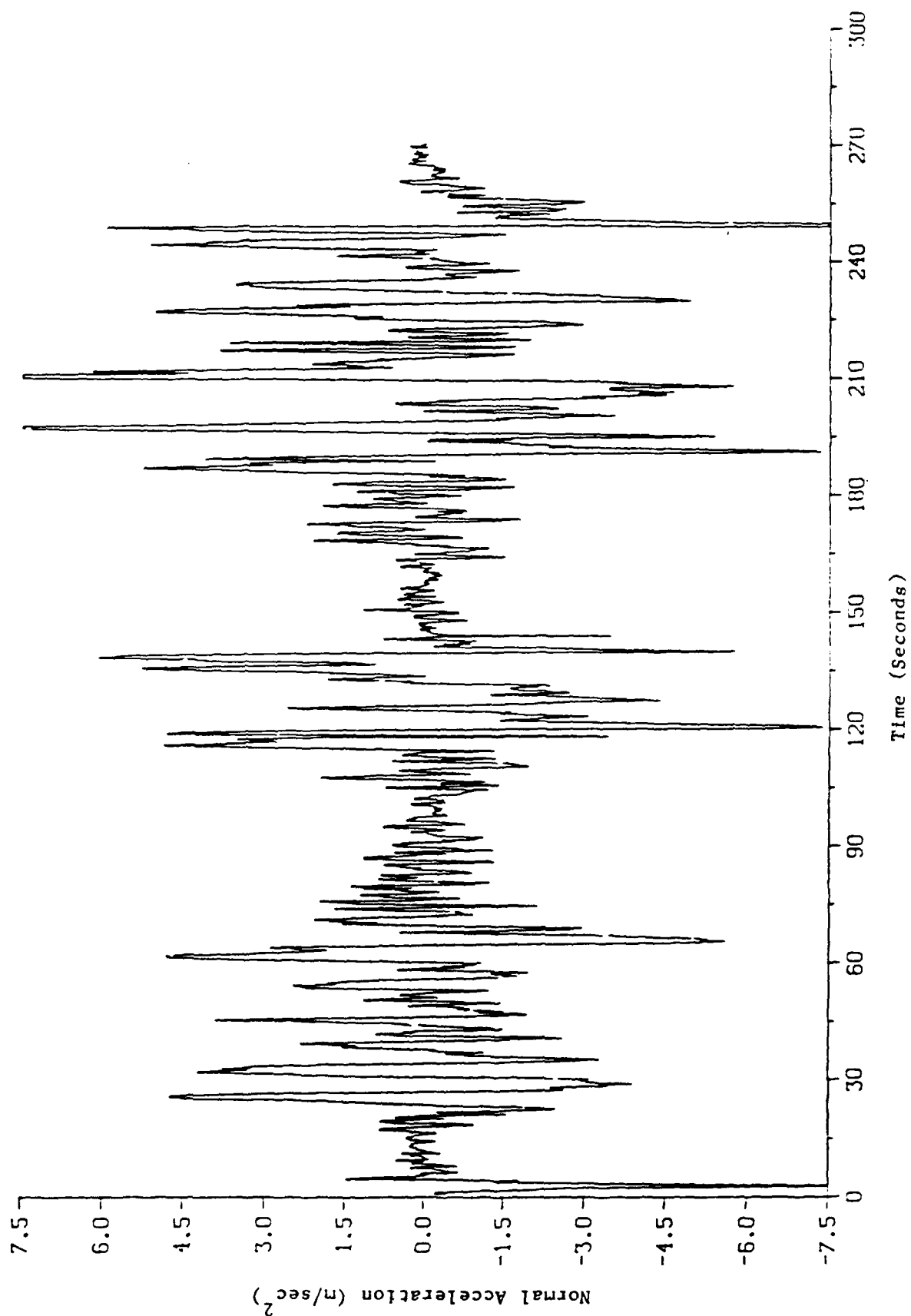
Figure 3. Estimated Target Speed

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Figure 4. Estimated Target Acceleration

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